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Intranight optical variability of radio-loud broad absorption line quasars

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ABSTRACT

We present the results of an optical photometric monitoring program of 10 extremely radio loud broad absorption line quasars (RL-BALQSOs) with radio-loudness parameter, R, greater than 100 and magnitude $g_i < 19$. Over an observing run of about 3.5-6.5 hour we found a clear detection of variability for one of our 10 radio-loud BALQSOs with the INOV duty cycle of 5.1 per cent, while on including the probable variable cases, a higher duty cycle of 35.1 per cent is found; which are very similar to the duty cycle of radio quiet broad absorption line quasars (RQ-BALQSOs). This low duty cycle of clear variability per cent in radio-loud sub-class of BALQSOs can be understood under the premise where BALs outflow may arise from large variety of viewing angles from the jet axis or perhaps being closer to the disc plane.

Key words: galaxies: active – galaxies: photometry – galaxies: jet – quasars: general

1 INTRODUCTION

Even after four decades of intensive research the physical nature of quasar variability is an open question. The quasar optical variability has long been a tool used to set limits on the size of the emitting regions, to constrain emission models, and to probe physical conditions close to the central black hole in active galactic nuclei (AGN). The microvariability phenomena found in radio-loud sub classes of AGN with $R^1 > 10$, is quite common and is widely believed to be connected to the conditions in relativistic jets. Since radio-quiet quasars (RQQSOs) lack jets of significant power and extent, the microvariability seen in them may arise from processes on the accretion disc itself, and thus could be used to probe the discs (e.g. Gopal-Krishna, Sagar & Wiita 1993). Our current understanding of optical microvariability is that only about ∼10 per cent of the radio-quiet quasars, which constitute ∼85−90 per cent of the quasar population, show microvariation, while rest of 10 per cent radio-loud (RL) sub-class shows about 35−40 per cent microvariability, when observed continuously for ∼6 hour (Gopal-Krishna et al. 2003; Stalin et al. 2004; Gupta & Joshi 2005). Recently, the microvariability studies have been extended to understand the nature of the radio-quiet quasar sub-class with broad absorption lines (BALs), the RQ-BALQSOs (Joshi et al. 2011), but still there has been a lack of systematic efforts towards the microvariability properties of their radio-loud counter part, i.e. radio-loud broad absorption lines, the RL-BALQSOs.

The BAL quasars are characterized by the presence of strong absorption troughs, attributed to material flowing outwards from the nucleus with velocities of 5000 to 50000 km s^{-1} (Green et al. 2001). They constitute about 10−15 per cent of optically selected quasars (e.g. Reichard, Richards, Hall et al. 2003; Hewett & Foltz 2003); which is generally interpreted as to represent the covering factor of an outflowing BAL wind. In addition, BALQSOs are primarily believed to belong the class of radio-quiet QSOs (Stocke et al. 1992). However with the advent of large comprehensive radio surveys, it has become clear that BALQSOs also constitute a significant fraction of luminous radio quasar population (Becker et al. 2000).

In term of microvariation of BALQSOs, recent compilation of microvariability studies by Carini et al. (2007) has pointed out that the BALQSOs may be an interesting class, as these shows about 50 per cent microvariation similar to the blazars, although their conclusion was based on just 6 RQ-BALQSOs. This was further investigated by Joshi et al. (2011) with three times larger sample size, and found that the true fraction of RQ-BALQSOs microvariation is just 2 out of 19, which was found similar to the usual low microvariability fraction of normal RQQSOs with observation lengths of about 4 hour. This result has rather provided support for models where radio-quiet BALQSOs do not appear to be a special case of the RQQSOs in terms of their microvariability properties. Further, it has also given support to the model, where BAL outflow appear to be closer to the disk plane (e.g. Elvis 2000).

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[1] Radio-loudness parameter, R, is defined as the ratio of radio [5 GHz] flux to the optical [2500 Å] flux.

In addition to probe the difference of microvariability properties among various class of AGN, there has been also considerable systematic efforts to investigate whether it depends on the radio-loudness of the AGN or not. For instance, de Diego et al. (1998) have performed photometric optical observations of a sample of 17 core-dominated radio-loud quasars (CRL-QSOs) and 17 radio-quiet quasars (RQQSOs), to compare their microvariability properties. They found that microvariation in RQQSOs may be as frequent as in CRL-QSOs, which was also augmented by a similar result of Ramírez et al. (2009). However, still there have been a lack of such systematic efforts to know whether or not this similarity also extend among the RQ-BALQSOs and RL-BALQSOs. This form the main motivation of our present work; to characterize for the first time microvariability properties of radio-loud BALQSOs and compare them with our earlier study of the radio-quiet BALQSOs (Joshi et al. 2011), using the same analysis and statistical method in both the cases. The investigation would also have an important implication in understanding the role of radio-loudness in microvariability properties and to get a clue whether the cause of microvariation in radio-loud and radio-quiet BAL quasars are similar or not.

Paper is organized as follows: in Section 2, we describe our sample selection criteria, our observations and the data reductions while in, Section 3, we describe our analysis and results. Finally, discussion and conclusion are given in Section 4.

2 SAMPLE SELECTION

We select a sample of 10 radio-loud BALQSO from the compilation of Shen et al. (2011) (their online Table 1) based on Sloan Digital Sky survey, Data Release 7 (SDSS DR−7; Abazajian et al. (2009)) quasar catalog (Schneider et al. 2010a), which satisfy two of our main selection criteria. First, the radio-loudness parameter, R, should be greater than 100. Here, the criterian chosen to limit radio-loudness parameter, R $>$ 100, was based on our requirement that, sample size should be large enough for the sake of better statistics and the selected sources should have reasonably high radio-loudness, so as to help in detection of any effect being mainly due to the difference in radio-loudness, between the two sub-classes i.e. the radio-loud BALQSOs verses the earlier studied radio-quiet BALQSOs (Joshi et al. 2011). Second, the source need to be bright enough with mag $g_i < 19$, so that even with a 1-2 m class telescope we could obtain a good enough signal-to-noise ratio (SNR) to detect fluctuations of < 0.02 mag with a reasonably good time resolution of < 10 minute.

We also limit the RL-BALQSOs to have absolute magnitudes $M_i < -24.5$, so that the flux contribution from the host galaxy can be assumed to be negligible (Miller et al. 1990). Our final sample consists of a total of 10 RL-BALQSOs, with 3 lobe and 7 core dominated radio morphology (Schneider et al. 2010b; Shen et al. 2011), as listed in Table 1. The whole sample covers a redshift range of $0.52 \leqslant z_{em} \leqslant 3.06$.

2.1 Photometric observations

The photometric monitoring is carried out by using the 1.3-m Devasthal fast optical telescope (hereafter 1.3-m DFOT) operated by Aryabhatta Research Institute of observational sciencES (ARIES), Nainital, India. DFOT is a fast beam (f/4) optical telescope with pointing accuracy better than 10 arcsec RMS (Sagar et al. 2011). The telescope is equipped with Andor CCD having 2048 × 2048 pixels, with pixel size of 13.5 micron resulting in the field of view of 18 arcmin on the sky. The CCD is read out with 31 and 1000 kHz speed, with the respective system RMS noise of 2.5, 7 e^- and gain of 0.7, 2 e^-/ADU (Analog to Digital Unit). The camera is cooled down thermoelectrically to $-85\ ^\circ$C. We perform continuous monitoring of each source for about 3.5−6.5 hour in SDSS−r passband at which our CCD system has maximum sensitivity. We observe each science frame for about 5−10 minute, to achieve typical SNR grater than 25. The typical seeing during our observing runs was 1.5−3.8 arcsec.

2.2 Data Reduction

All image pre-processing steps, i.e. bias subtraction, flat-fielding and cosmic-ray removal are carried out using the standard tasks available in the data reduction software IRAF [2]. The instrumental magnitudes of the comparison stars and the target source are obtained from the data by using Dominion Astronomical Observatory PhotometryII (DAOPHOT II) [3] software to perform the concentric circular aperture photometric technique (Stetson 1987). Aperture photometry is carried out with four aperture radii, 1, 2, 3, & 4 times of the full width at half maximum (FWHM). Utmost caution has been taken to deal with the seeing and for that, we have taken the mean FWHM of 5 fairly bright stars on each CCD frame in order to choose the aperture for the photometry of that frame. The data reduced with different aperture radii are found to be in good agreement. However, we adopted the aperture radii of ∼2×FWHM for our final results as it has almost always provided the best signal-to-noise ratio.

To derive the Differential Light Curves (DLCs) of quasar, we have selected two steady comparison stars from the same field, on the basis of their proximity in both location and magnitude to the quasar. The locations of the two best comparison stars for each RL-BALQSO is given in columns 3, 4 of Table 2. The typical colour differences $g-r$ for our quasar-star and star-star pairs are close to unity (see column 7, Table 2). A detailed investigation quantifying the effect of colour differences by Carini et al. (1992) & Stalin et al. (2004) shows that the effect of colour differences of this amount on DLCs will be negligible for a specific band.

We employed a mean clip algorithm on the comparison star-star DLCs, so as to remove any outliers, i.e. the sharp rise or fall of the DLC over a single time bin which may arise due to improper removal of cosmic rays or some unknown instrumental cause, above the 3σ from the mean. The

[2] Image Reduction and Analysis Facility (http://iraf.noao.edu/)

[3] Dominion Astrophysical Observatory Photometry

Table 1. Properties of the observed radio-loud BALQSOs.

Object	$\alpha_{2000.0}$	$\delta_{2000.0}$	g_i	M_i	z_{em}	R^a	Type^b
J004323.42−001552.4	$00^h\ 43^m\ 23.42^s$	$-00^\circ\ 15'\ 52.48''$	18.80	−27.0	2.797	597.97	2
J082231.53+231152.0	$08^h\ 22^m\ 31.53^s$	$+23^\circ\ 11'\ 52.00''$	17.94	−25.2	0.653	117.12	2
J085641.56+424253.9	$08^h\ 56^m\ 41.56^s$	$+42^\circ\ 42'\ 53.90''$	18.83	−27.9	3.061	198.53	1
J092913.96+375742.9	$09^h\ 29^m\ 13.96^s$	$+37^\circ\ 57'\ 42.90''$	18.32	−27.8	1.915	147.51	1
J095327.95+322551.6	$09^h\ 53^m\ 27.95^s$	$+32^\circ\ 25'\ 51.00''$	17.77	−27.7	1.574	278.62	2
J112938.46+440325.0	$11^h\ 29^m\ 38.46^s$	$+44^\circ\ 03'\ 25.00''$	18.25	−27.8	2.211	250.81	1
J115944.82+011206.9	$11^h\ 59^m\ 44.82^s$	$+01^\circ\ 12'\ 06.00''$	17.58	−28.4	2.002	471.59	1
J121539.66+090607.4	$12^h\ 15^m\ 39.66^s$	$+09^\circ\ 06'\ 07.40''$	18.37	−27.9	2.722	156.77	1
J122848.21−010414.4	$12^h\ 28^m\ 48.21^s$	$-01^\circ\ 04'\ 14.40''$	18.31	−28.1	2.655	119.09	1
J160354.14+300208.6	$16^h\ 03^m\ 54.14^s$	$+30^\circ\ 02'\ 08.60''$	18.16	−27.6	2.031	185.66	1

[a] Ratio of the radio [5 GHz] flux to the optical [2500Å] flux taken from SDSS DR7 (Schneider et al. 2010a).
[b] Quasar type: 1=core-dominant; 2=lobe-dominant (radio morphology classification following Jiang et al. 2007).

data points corresponding to exposure resulting in such outliers are also removed from the respective quasar-star DLCs as well. However, we should stress here that such outliers in our comparison star-star DLCs were usually not present and never exceeded two data points. Finally, the statistical analysis of microvariability is performed on the quasar-star and star-star DLCs, freed from such outliers, as shown in Figure 1, 2.

3 ANALYSIS & RESULTS

So far in the literature, the most commonly used statistics to quantify the intra-night optical variability (INOV) of DLCs, is the "*C-statistics*" (Romero, Cellone & Combi 1999), which is the ratio of observational scatter of quasar-star and star-star DLCs. However, de Diego (2010) has pointed out that the C is not a proper statistics, as the nominal confidence limit (i.e. C>2.57) for the presence of variability with 99% confidence, is too conservative.

de Diego (2010) has shown that the other alternatives to the C-statistics are the one-way analysis of variance (ANOVA), χ^2-test and $F-$test, which are much powerful statistical tests to quantify the presence of microvariability. We noticed that for an appropriate use of ANOVA, the number of data points in the DLC needs to be large enough so as to have many points in each subgroup used for the analysis; however, this is not possible for our observations as we have typically only around 30-40 data points in our light curves. In addition, for the appropriate use of a χ^2- test, the errors of individual data points need to have Gaussian distribution and those errors should be accurately estimated. It has been claimed in the literature that errors returned by photometric reduction routines in IRAF and DAOPHOT are usually underestimated, often by factors of 1.3−1.75 (Gopal-Krishna et al. 2003; Sagar et al. 2004; Bachev et al. 2005; Goyal et al. 2012), which make use of a χ^2- test less desirable for such real photometric light curves. Therefore, to quantify the INOV in DLCs, we prefer the proper statistics that is reasonable to employ for differential photometry, the $F-$test (de Diego 2010).

Although the F-test is certainly better than the C-test, it should be noted that for the F-test to give a truly reliable result, the error due to random noise in the quasar-star and star-star DLCs should be of a similar order, apart from any additional scatter in the quasar-star DLC due to possible QSO variability. Joshi et al. (2011) have pointed out that the standard $F-$test statistic does not account for the brightness difference in between quasar and comparison star as well as for the photometric error returned by the image reduction routines, which can result the false alarm detection(non-detection) of variability. For instance, if both comparison stars are brighter(fainter) than the monitored quasar, then a false alarm detection (non-detection) is possible due to the very small(large) photon noise variance of the star-star DLC compared to the quasar-star DLCs as demonstrated in Joshi et al. (2011). Although we have tried to select our non-variable comparison star in proximity to both position and magnitude to the quasar, but it is very difficult to find the same for all the quasars. So here we have used the "scaled $F-$test" statistic, as is suggested by Joshi et al. (2011), to compute our $F-$value as follows:

$$F_1^s = \frac{Var(q-s1)}{\kappa \times Var(s1-s2)}, \qquad F_2^s = \frac{Var(q-s2)}{\kappa \times Var(s1-s2)} \tag{1}$$

with κ, defined as,

$$\kappa = \left[\frac{\sum_{\mathbf{i=0}}^{\mathbf{N}} \sigma_{i,err}^2(q-s)/N}{\sum_{\mathbf{i=0}}^{\mathbf{N}} \sigma_{i,err}^2(s1-s2)/N} \right] \equiv \frac{\langle \sigma^2(q-s) \rangle}{\langle \sigma^2(s1-s2) \rangle}, \tag{2}$$

where $\sigma_{i,err}^2(q-s)$ and $\sigma_{i,err}^2(s1-s2)$ are, respectively, the errors on individual data points of the quasar-star and star-star DLCs as returned by the DAOPHOT routine. Here, the term κ is a scaling factor, applied to the variance of the star-star DLC. Firstly, this scaling factor will take care of the difference in magnitude between the QSO and star in quasar-star and star-star DLCs. Secondly, it is free from the problem of uncertain error underestimation by DAOPHOT/IRAF routines reported by many other authors, because our scaling factor depends on the ratio of the averaged squared errors and hence any factor with which errors are either underestimated or overestimated will be canceled out. Therefore, we report our final results based on this *scaled F−test* (defined by F^s).

We also note that, in standard F-test, the F-value is a ratio of the two sample variance, with the assumption

Table 2. Positions and magnitudes of the radio-loud BALQSOs and the comparison stars.

IAU Name (1)	Date dd.mm.yy (2)	R.A.(J2000) (h m s) (3)	Dec.(J2000) (° ′ ″) (4)	g (mag) (5)	r (mag) (6)	g-r (mag) (7)
J004323−001552	14.11.2012	00 43 23.43	−00 15 52.4	18.76	18.47	0.29
S1		00 43 45.79	−00 19 31.6	16.99	16.55	0.44
S2		00 433 9.19	−00 20 24.6	16.88	16.49	0.39
J082231+231152	28.01.2012	08 22 31.53	+23 11 52.0	17.93	17.68	0.25
S1		08 23 09.66	+23 14 42.4	17.37	16.85	0.52
S2		08 22 12.58	+23 05 07.4	18.15	16.85	1.30
J082231+231152	14.11.2012	08 22 31.53	+23 11 52.0	17.93	17.68	0.25
S1		08 23 01.30	+23 18 05.1	18.54	18.12	0.42
S2		08 22 18.56	+23 16 50.9	19.49	18.06	1.44
J085641+424254	22.02.2012	08 56 41.56	+42 42 53.9	18.81	18.50	0.31
S1		08 56 31.48	+42 37 51.2	17.77	17.49	0.28
S2		08 56 19.09	+42 35 09.5	18.12	17.37	0.75
J092914+375743	23.02.2012	09 29 13.96	+37 57 42.9	18.28	18.05	0.23
S1		09 28 44.88	+37 50 25.0	18.64	17.79	0.85
S2		09 28 44.88	+37 50 25.0	18.64	17.79	0.85
J095327+322551	29.01.2012	09 53 27.95	+32 25 51.6	17.77	17.36	0.41
S1		09 52 59.50	+32 29 47.0	18.21	17.12	1.09
S2		09 52 55.29	+32 33 30.3	17.91	17.30	0.61
J112938+440325	24.02.2012	11 29 38.46	+44 03 25.0	18.22	18.12	0.10
S1		11 30 15.26	+43 54 52.1	17.80	17.15	0.65
S2		11 30 02.97	+44 07 12.9	18.15	17.02	1.13
J115944+011206	28.01.2012	11 59 44.82	+01 12 06.9	17.58	17.25	0.33
S1		11 59 48.28	+01 19 38.6	17.55	17.16	0.39
S2		12 00 07.71	+01 10 33.0	17.93	17.38	0.56
J121539+090607	23.02.2012	12 15 39.66	+09 06 07.4	18.39	18.26	0.13
S1		12 16 05.93	+08 59 03.2	17.94	17.56	0.38
S2		12 15 38.76	+09 03 19.9	18.39	17.64	0.76
J122848−010414	22.02.2012	12 28 48.21	−01 04 14.5	18.28	18.17	0.11
S1		12 28 21.82	−01 02 36.4	19.31	17.85	1.46
S2		12 28 22.35	−01 01 19.2	17.86	17.65	0.22
J160354+300208	15.05.2012	16 03 54.15	+30 02 08.6	18.13	17.96	0.17
S1		16 04 30.55	+30 03 03.7	18.80	17.66	1.14
S2		16 03 44.29	+30 02 11.2	18.70	17.25	1.45

that error-bar in both the samples is of similar order. In other words, more specifically when divided by σ^2 the variance will be distributed according to χ^2 distribution, and hence F-distribution by definition consists of the ratio of two χ^2 distributions, which is finally used to derive its probability distribution. Our *scaled F−test*, with κ term, also amount to the ratio of two χ^2 distribution by assigning $\sigma^2 = \sum \sigma^2_{i,err}/(N-1)$ as averaged error. The only difference here, compared to the standard F-test, is that the error-bar appearing in the χ^2 numerator (i.e. of quasar-star DLC) and denominator (i.e. of star-star DLC) do differ due to any brightness difference between quasar and its comparison stars. Therefore, in *scaled F−test* unlike the standard F-test, σ^2 term of the numerator and denominator though does not exactly get canceled out, but still do preserve its genuine F-distribution.

F values computed by Eq 1, are compared individually with the critical F value, $F^{(\alpha)}_{\nu_{QS}\nu_{SS}}$, where α is the significance level set for the test, and ν_{QS} and ν_{SS} are the degrees of freedom of the quasar-star and star-star DLCs, respectively. The smaller the α value, the more improbable that the result be produced by chance. For the present study, we have used the significance levels, $\alpha = 0.01$ and 0.05, which corresponds to confidence levels of greater than 99 and 95 per cent respectively. If F is larger than the critical value, the null hypothesis (i.e. no variability) is discarded. Thus, for variability status we prefer to compare the $F-$value corresponding to quasar-star1 and quasar-star2 DLCs (i.e. F^s_1 & F^s_2) from Eq. 1, separately with the critical F value, as if one DLC indicates variability and other doesn't, these mixed signals bring into question the reality of the putative variability. So, a quasar is marked as *Variable* ('V') for a F-value $\geqslant F_c(0.99)$, which corresponds to a confidence level $\geqslant 0.99$; *Probably variable* ('PV') if the F-value is between $F_c(0.95)$ and $F_c(0.99)$; *Non variable* ('NV') if the F-value is less than $F_c(0.95)$. Finally, we assign a source as; of class variable (i.e. 'V') if both the quasar-star1 and quasar-star2 states it as 'V'; of class probably variable (i.e 'PV') if either both DLCs show it as 'PV', or one of it as 'PV' and other as 'V'; of class non variable (i.e. 'NV') if any one of the quasar-star1 or quasar-star2 DLC show it as non variable (i.e. 'NV').

The DLCs of our radio-loud BALQSOs sample are shown in Figure 1, 2 and the corresponding results of our

Table 3. INOV results for the radio-loud BALQSOs.

RL-BALQSO	Date dd.mm.yy	T hrs	N	*scaled F−test* F_1^s,F_2^s	$F_c(0.95)$	$F_c(0.99)$	Variability?[a]	$\sqrt{\kappa}$[b]	$\sqrt{\langle\sigma^2_{i,err}\rangle}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
J004323.42−001552.4	14.11.2012	6.73	38	0.76,0.94	1.73	2.18	NV(NV, NV)	3.56	0.03
J082231.53+231152.0	28.01.2012	4.04	33	2.35,2.44	1.80	2.32	V(V ,V)	1.06	0.02
J082231.53+231152.0	14.11.2012	4.21	23	0.76,0.93	2.05	2.78	NV(NV, NV)	2.31	0.02
J085641.56+424253.9	22.02.2012	3.51	25	1.40,1.13	1.98	2.66	NV(NV, NV)	1.67	0.01
J092913.96+375742.9	23.02.2012	3.88	44	0.78,1.08	1.66	2.06	NV(NV, NV)	1.08	0.02
J095327.95+322551.6	29.01.2012	4.18	34	1.13,1.26	1.79	2.29	NV(NV, NV)	1.14	0.01
J112938.46+440325.0	24.02.2012	3.40	40	1.89,1.86	1.70	2.14	PV(PV, PV)	1.75	0.01
J115944.82+011206.9	28.01.2012	4.89	44	2.03,1.92	1.66	2.06	PV(PV, PV)	1.04	0.01
J121539.66+090607.4	23.02.2012	4.21	32	0.82,0.62	1.82	2.35	NV(NV, NV)	1.77	0.02
J122848.21−010414.4	22.02.2012	4.16	48	1.28,0.86	1.62	1.99	NV(NV, NV)	1.18	0.01
J160354.14+300208.6	15.05.2012	3.49	36	2.35,1.91	1.76	2.23	PV(V ,PV)	1.49	0.02

[a] V=variable, i.e. confidence $\geqslant 0.99$; PV=probable variable, i.e. $0.95-0.99$ confidence; NV =non-variable, i.e. confidence < 0.95. Variability status values based on quasar-star1 and quasar-star2 pairs are separated by a comma.
[b] Here $\kappa = \langle\sigma^2(q-s)\rangle/\langle\sigma^2(s1-s2)\rangle$ (as in Eq. 2), is used to scale the variance of star-star DLCs for the *scaled F−test*.

analysis are summarized in Table 3. In the first four columns, we list the object name, date of observation, the duration of our observation, and the number of data points (N_{points}) in the DLC. The column five gives the *scaled F−test* values corresponding to both quasar-star1 and quasar-star2 DLCs. The columns six, seven mention the critical F-value for the corresponding 95 per cent and 99 per cent significance level. In column eight, we give the variability status of our source, based on the *scaled F−test* for both the quasar-star1 and quasar-star2 DLCs. Column nine lists the square root of scaling factor, $\sqrt{\kappa}$, where $\kappa = \langle\sigma^2(q-s)/\sigma^2(s1-s2)\rangle$ (as in equation 1), and has been used to scale the variance of the star−star DLCs while computing the F value in the *scaled F−test*. The last column gives our photometric accuracy, $\sqrt{\langle\sigma^2_{i,err}\rangle}$ in the quasar−star DLCs, which is typically of 0.01-0.03 mag.

3.1 The INOV duty cycle (DC)

The duty cycle of INOV was computed as is given by Romero, Cellone & Combi (1999),

$$DC = 100\frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} N_i(1/\Delta t_i)}{\sum_{\mathbf{i=1}}^{\mathbf{n}}(1/\Delta t_i)}\text{percent} \tag{3}$$

where $\Delta t_i = \Delta t_{i,obs}(1+z)^{-1}$ is the duration of the monitoring session of a source on the i^{th} night, corrected for its cosmological redshift, z. Since the observing run time for a given source is not same for different nights observation, so the computation of DC has been weighted by the actual monitoring duration Δt_i on the i^{th} night. Here, N_i was set equal to 1 if INOV was detected, otherwise $N_i = 0$.

In 8 nights monitoring (i.e. for ∼46 hour) of our 10 RL-BALQSOs, we find a clear signature of variability for one RL-BALQSO resulting in INOV duty cycle (DC) of 5.1 per cent. While on including the three sources assigned as probable variable (‘PV’, class), the DC increases to 35.1 per cent.

Here, it is also worth comparing the DC of RL-BALQSOs with our earlier study of 19 RQ-BALQSOs for microvariability properties (Joshi et al. 2011). For that, we have computed the INOV DC value of RQ-BALQSOs sample, by using Eq. 3. An INOV DC of 6.41 and 34.28 per cent was found respectively for clear detection of variability (two out of 19 DLCs) and probably variable cases (six out of 19 DLCs), which is almost similar to our above DC of RL-BALQSOs.

4 DISCUSSION & CONCLUSIONS

Soon after the discovery of quasars, their behavior of changing flux in minutes to hours and amplitude from few tenth to a few magnitude i.e. the microvariability, was reported (Matthews & Sandage 1963). Thereafter, plenty of efforts have been made to correlate it with several other properties, such as quasar orientation, radio loudness and polarization, driving the microvariation in various sub-classes of AGN. The emerging picture is that the microvariability does not occur as often in radio-quiet objects as it does in radio-loud sources (Gopal-Krishna et al. 2003; Stalin et al. 2004; Carini et al. 2007). However, a multiband monitoring study of 22 radio-quiet and 22 core dominated radio-loud (CRL) quasars by Ramírez et al. (2009), has confirmed that the frequency of microvariability in both these quasar sub-classes are same; similar to the earlier results found by de Diego et al. (1998). Recently, Goyal et al. (2012) has investigated the role of optical polarization along with the relativistic beaming in microvariability property for a large sample of 21 core dominated quasars (CDQs), consisting of 12 low polarization (LP) and 9 high polarization (HP) QSOs. With the INOV duty cycle of 28 per cent and 68 per cent respectively for LPCDQs and HPCDQs, they concluded that

the relativistic beaming is normally not a sufficient condition, but high optical polarization is also a necessary condition for strong INOV.

In general, the microvariability seen in radio-loud objects is now widely believed to come from turbulence in a relativistic jet pointed at or nearly along our line of sight. However, in the case of radio-quiet objects, the jets are weaker than radio-loud jets or quenched near their origin point due to the effects of black hole spin (Wilson & Colbert 1995; Blandford 2000) or magnetic configurations (Meier 2002). To know which mechanism among these various possibilities is at play for the origin of microvariability on different sub-classes of AGN, the constraints obtained by extending the microvariability studies to other remaining AGN sub-class such as BALQSOs have given important clues (see e.g. Joshi et al. 2011). For instance, the early evidence from spectro-polarimetry of BALQSOs give an idea that they are viewed closer to the disk plane i.e. nearly edge-on (e.g. Goodrich & Miller 1995). It also supports the models where outflow comes closer to the disk plane (e.g. Elvis 2000). It can be a clue to understand the radio-loud/radio-quiet dichotomy as the BAL quasars appeared to be exclusively radio-quiet, where outflows are not well collimated. Later Brotherton et al. (2006) have shown that BALQSOs are viewed at a large variety of viewing angles ($\sim 15^\circ$ from the jet axis to nearly edge-on). Constrained by radio flux density variability to lie within 35° of a relativistic jet, give rise to a new population of polar BALQSO i.e. those viewed perpendicular to the disk (e.g. Zhou, Wang, Wang, Wang, Yuan & Lu 2006; Ghosh & Punsly 2007; Montenegro-Montes, Mack, Vigotti et al. 2008; Doi, Kawaguchi, Kono et al. 2009), where outflows are confined to well-collimated relativistic jets.

In these contexts, here we have presented our results of intranight optical variability observations of 10 extremely radio-loud (i.e. R> 100) BALQSOs, observed mostly in the first half of year 2012. These are the first extensive observations of radio-loud sub-class of BALQSOs with an aim to probe their microvariability nature. In other words, we have investigated the effect of presence of BAL as well as radio-loudness on microvariability properties. The application of proper statistics, i.e. the "*scaled F−test*" (Joshi et al. 2011) has allowed us to find the genuine confirmed INOV DC of 5.1 per cent (one variable DLC out of total 10), which becomes 35.1 per cent if we also include the three probable variable (i.e. 'PV') cases as well. This DC is free from any spurious cause, as could be present at times while using the standard F-test i.e. introduced by the brightness difference in quasar and its comparison star (e.g. Section 3), since we have used *scaled F−test*, described in detail in Joshi et al. (2011). Having used the same statistical and analysis method, both in this work and Joshi et al. (2011), where they studied microvariation properties of 19 radio-quiet BALQSOs, we carried out the comparison of these two results and found that our resulting INOV DC of 5.1 per cent matches with their result of 6.41 per cent fraction (where they found out of 19 only 2 DLCs as variable, also see Section 3.1). This suggest that radio-loudness has not any significant role at least in the case of microvariability properties of BALQSOs, but larger sample size of radio-loud BALQSOs will help to say about it more firmly.

As a general implication, if we would have also got high DC of microvariation in our RL-BALQSOs, such as found by Zhou et al. (2006) & Ghosh & Punsly (2007) based on their radio monitoring, then it would have suggested that the BAL outflow are aligned very close to the jet axis (about < 35 deg) which may be responsible for the higher DC due to Doppler boosting. On the other hand, the common wind based model of BAL outflow demand the outflow to be preferentially equatorial when the accretion disk is almost edge on (e.g. Elvis 2000), predicting the low DC as is also suggested by our this investigation. Though only with such microvariability studies, it may be difficult to distinguish clearly among many possibilities in a quantitative manner; but with our this study we certainly could conclude that the microvariation of both radio-loud and radio-quiet BALQSOs are very similar, and the level of microvariation occurrence in both cases is quite low as is usually found for radio-quiet QSOs, the theoretical implication of which for AGN unification scheme needs further exploration.

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APPENDIX A: BRIEF NOTES ON INDIVIDUAL SOURCES

A1 J004323.42−001552.5

J004323.42−001552.5 is a high redshift (i.e. z=2.797) BALQSO with a balnicity index[4](BI) of 591.10 km s^{-1} (Gibson et al. 2009). It appears as non-variable according to our *scaled F−test* with an observation length of 6.73 hr.

A2 J082231.53+231152.0

J082231.53+231152.0 is a low redshift (i.e. z=0.653), Mg II low ionization broad absorption line (loBAL) quasar (Zhang et al. 2010). This source has been monitored twice, firstly on the night of 28 January 2012 for about 4.04 hr and secondly on the night of 14 November 2012 for about 4.21 hr. On applying the *scaled F−test* statistics, this source

[4] The Balnicity Index metric is defined as

$$BI = -\int_{25000}^{3000} \left[1 - \frac{f(v)}{0.9}\right] C dv. \quad \text{(A1)}$$

Here, the limits of the integral are in units of $km\ s^{-1}$, $f(v)$ is the normalized flux as a function of velocity displacement from line center. The constant $C = 0$ everywhere, unless the normalized flux has satisfied $f(v) < 0.9$ continuously for at least 2000 km s^{-1}, at which point it is switched to $C = 1$ until $f(v) > 0.9$ again. Based on this definition, objects are classified as BALQSOs if their $BI > 0$ km s^{-1}.

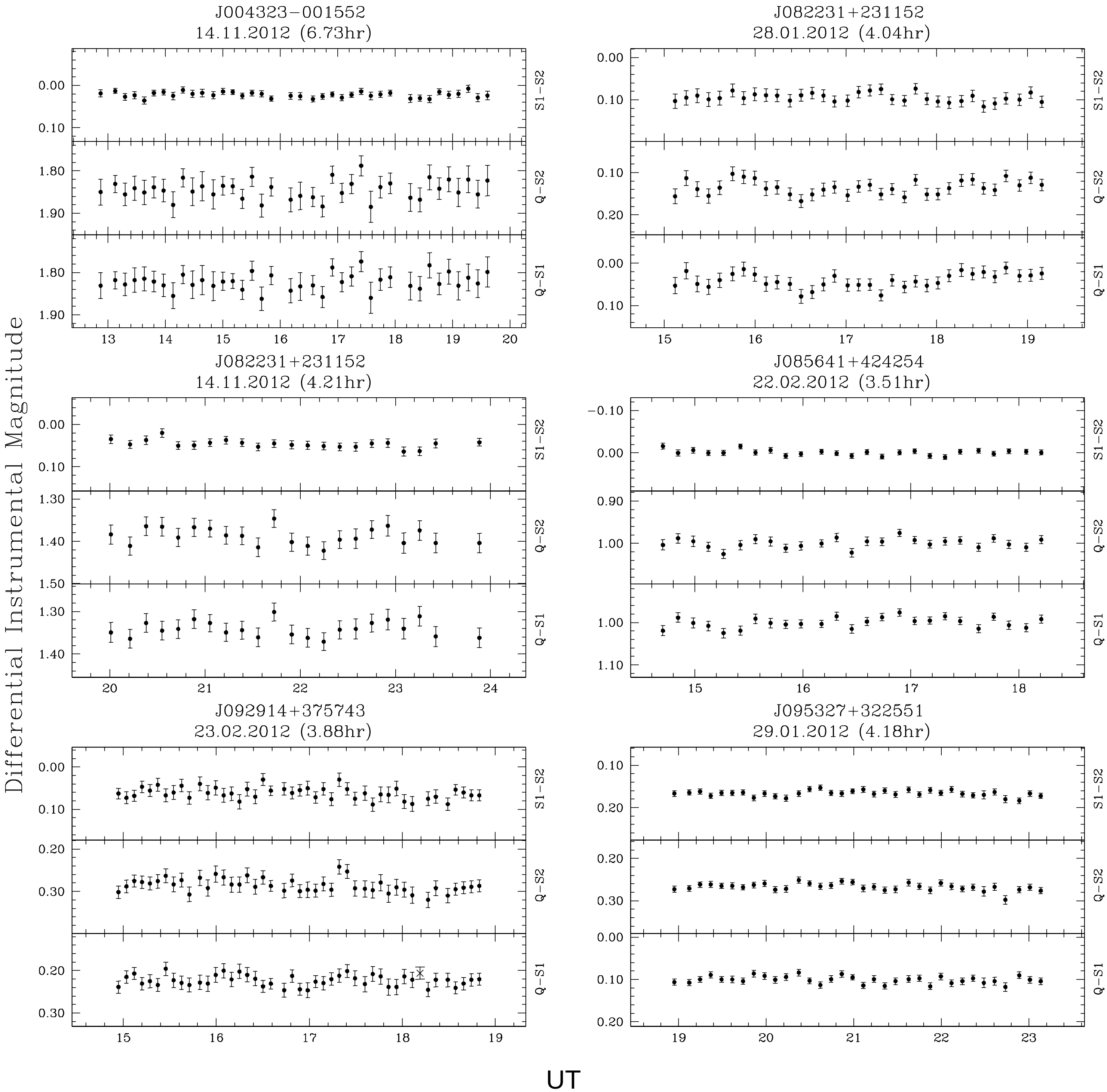

Figure 1. Differential light curves (DLCs) for the radio-loud BALQSOs in our sample. The name of the quasar and the date and duration of the observation are given at the top of each night's data. The upper panel gives the comparison star-star DLC and the subsequent lower panels give the quasar-star DLCs as defined in the labels on the right side. Any likely outliers (at $> 3\sigma$) in the star-star DLCs are marked with crosses, and the data corresponding to such flagged exposure are also removed from quasar-star DLC, for the final analysis.

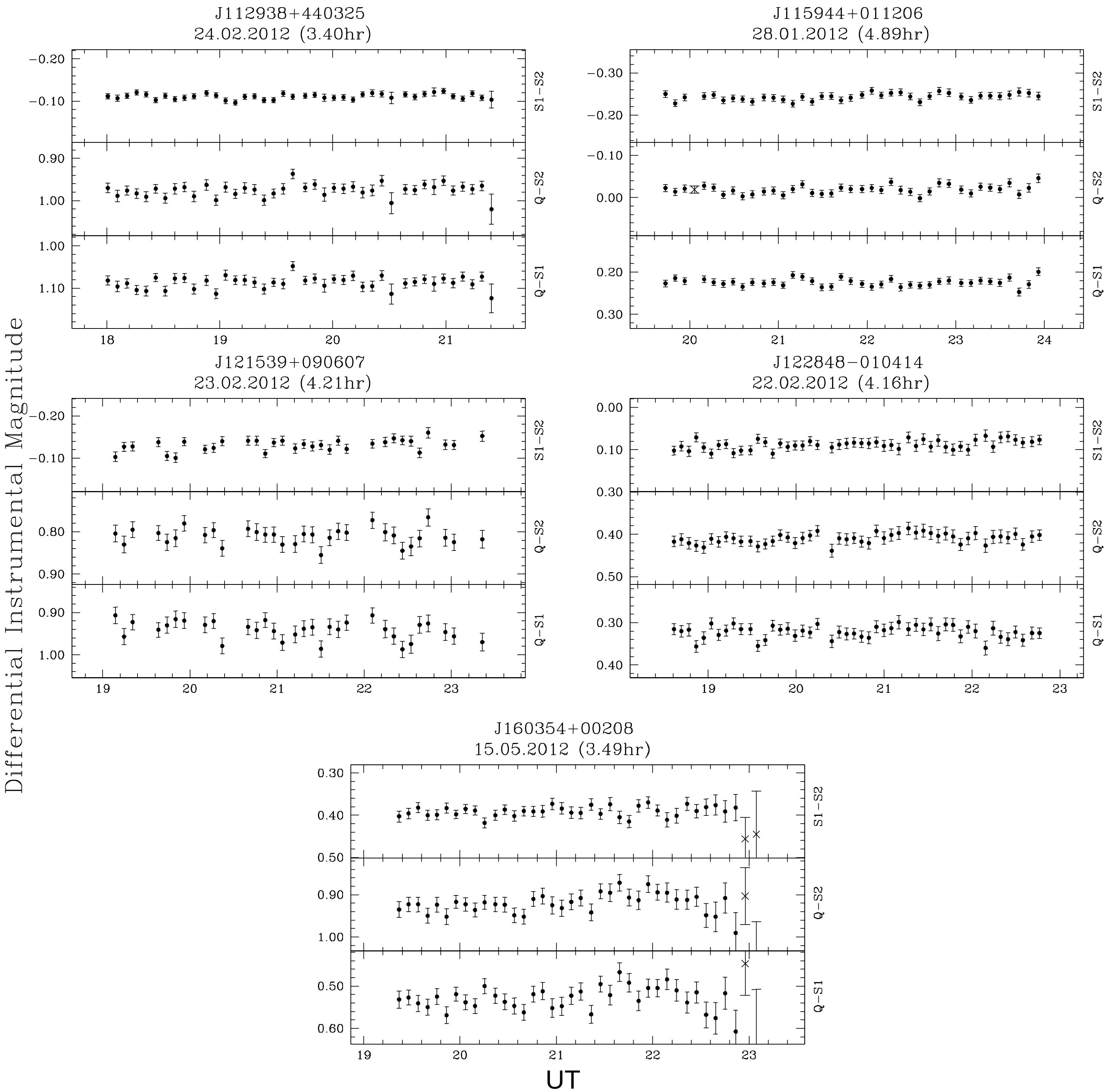

Figure 2. Same as in Figure 1.

has indicated a clear signature of microvariability in its first DLC lasting ∼4.04 hr while appeared as non-variable in its second DLC (e.g see Table 3). This makes it a promising candidate for future INOV monitoring.

A3 J085641.56+424253.9

J085641.56+424253.9 is a C IV high ionization broad absorption line (HiBAL) quasar, with a balnicity index of 820.60 km s^{-1} (Trump et al. 2006; Gibson et al. 2009). This BALQSO is also identified as a high redshift, z=3.061, weak emission line quasar by Diamond-Stanic et al. (2009). We observed this source for ∼3.51 hr duration for which the sta-

tistical analysis of its DLC does not give any clue of rapid variability.

A4 J092913.96+375742.9

This source has a massive black hole of mass $8.9\times10^9 M_\odot$, estimated using its Mg II line width (see e.g. Shen et al. 2008). This source is a HiBAL with BI value corresponding to its C IV line is 1204.7 km s^{-1}. We found this source to be non-variable during our 3.9 hr observation.

A5 J095327.95+322551.6

This source is a flat spectrum radio quasar type with a 4.8 GHz flux density of 184mJy (Healey et al. 2007). This source is detected as BAL in Gibson et al. (2009) SDSS DR-5 BAL quasar catalog, with a C IV balnicity index of 267.0 km s^{-1}. This source has not shown any signature of microvariability, for an observing run of 4.18 hr.

A6 J112938.46+440325.0

This BAL quasar has a C IV BI value of 806.5 km s^{-1} (Gibson et al. 2009) and has a massive black hole of, $1.32\times10^{10} M_\odot$ as estimated by using the Mg II line width (Shen et al. 2008). This source was found to be probably variable during the course of our 3.40 hr observation, which makes it a potential source for further microvariability study.

A7 J115944.82+011206.9

This source, also known as, PKS 1157+014, has long been known to possess a 21 cm absorption at z_{abs} = 1.94 (Wolfe et al. 1986) associated with the DLA (Colbert & Malkan 2002). Stocke et al. (1984) found it as unresolved point source in 488MHz VLA observation, with flux value of 108mJy. It is a HiBAL with balnicity index of 299.3, 632.9 km s^{-1}, respectively for Si IV and C IV (Gibson et al. 2009). This source is a promising candidate for future investigation as it appears probably variable for our observing run of 4.89 hr.

A8 J121539.66+090607.4

This source is a member of large bright quasar survey and is also known as LBQS 1213+0922. It has a massive black hole of mass $5.12 \times 10^9 M_\odot$ estimated by using the C IV line width by Shen et al. (2008). This is a narrow trough high ionization BAL (i.e. nHiBAL) QSO with BI value 116.30 km s^{-1}, estimated by C IV line. During the monitoring of this source, few exposures got corrupted (about maximum 8-9) due to some technical problem, which we have removed manually resulting in few gaps in its DLC. Over the monitoring duration of $\sim$4.21 hr, we found this source to be non-variable.

A9 J122848.21−010414.4

This is a HiBAL quasar, with BI value of 17.0 km s^{-1}, corresponding to the C IV line. It appears as non-variable according to our *scaled F−test* with an observation length of 4.16 hr.

A10 J160354.14+300208.6

This is a HiBAL quasar with a massive black hole of mass $1.46 \times 10^9 M_\odot$ estimated by using the Mg II line (Shen et al. 2008). Its BI value is 84.7, 480.0 km s^{-1}, respectively for Si IV and C IV line. Over an observation length of 3.49 hr, we found it as probably variable (i.e. 'PV'), which makes it a potential candidate for further microvariability study.

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